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SYNCHRONISM AND HETEROCHRONISM OF SYNKINESIS IN MAN

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ABSTRACT. The potentials of arbitrary synchronization of synkinesis in man is studied, as are elementary flexing and extension single-joint movements of the different links in the body.

Interest in the anatomical structure and peculiarities in the functioning /138 of the links of the body can, today, be common to anatomists and physiologists, as well as to engineers, mathematicians, or designers.

Wide-ranging study of the functional peculiarities of the man-operator is very necessary in order to reach a complete determination of the potentials of man-machine systems, to optimize the relationship between human capabilities and the operational properties of the machine.

The terms "simultaneous and nonsimultaneous movements" are widely used in practice. This characteristic of movements is so strongly entrenched in the vocabulary that the question is raised of whether or not simultaneous, or synchronized, movements made by man at will seem, at first glance, to be artificial.

Investigation of the synchronization of synkinesis also is of theoretical interest in connection with the evaluation of the coordination potentials of human movements, because it reveals the peculiarities of controlling the different links in the human motor apparatus.

This investigation attempted to determine the possible degree of synchronization of the elementary, symmetrical, and unilateral movements made by the links in the human lower and upper extremities.

Investigation Procedure

The task posed for investigation while different parts of the body were moving was to perform synkinesis at any convenient tempo, with particular attention given to the simultaneity of closing of contacts at the end of each movement. Once preliminary tests were out of the way, we proceeded to carry out the assignment. A K-105 oscillograph was used to make graphic recordings of the

times of beginning, duration, and of contact individually for each link in the human body involved in synkinesis. The installation shown in Figure 1a was assembled for this purpose.

A movable contact, 1, was fastened to the links of the body completing synkinesis studied (see Figure 1). The number of such links usually was 2. Flexing-extending movements in the following joints were studied: talocrural, knee, hip of right and left leg, as well as the shoulder, elbow, radiocarpal and metacarpal-phalangeal joints of the right and left arms. /139

All experiments were divided up into several series, in each of which individual, special research tasks were carried out. An example of an oscillogram recording is shown in Figure 1b.

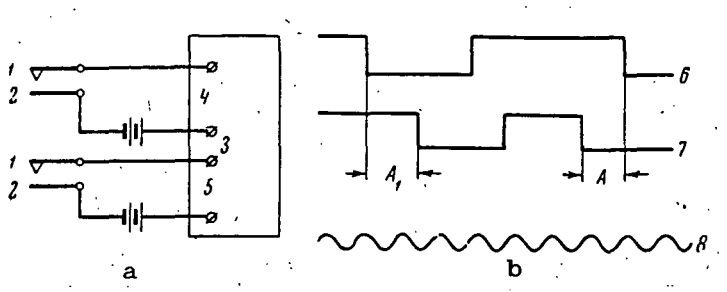

Figure 1. Diagram of an installation for recording the degrees of synchronism of synkinesis in man. a - block diagram of the installation; b - example of oscillogram recording; A and A_1 - intervals characterizing the heterochronism of synkinesis; 1 - movable contacts fastened to moving body links; 2 - fixed contacts; 3 - type K-105 oscillograph; 4 - 5 - inputs to channels I and II of the oscillograph; 6 - 7 - oscillograms from channels I and II; 8 - 0.002 second time marker.

The degree of synchronization of symmetrical synkinesis was investigated in the first series of experiments. Man, as we know, can be conditionally said to have two planes of symmetry; the vertical, or right-left side (YY_1), and the horizontal, or lower-upper (XX_1) (Figure 2). So the first series of experiments included investigation of the degree of synchronization of the right-left side movements: hand-hand (Aa), forearm-forearm (Bb), shoulder-shoulder (Cc). The mutually harmonious movements of the links of the lower extremities were studied correspondingly: foot-foot (A_1a_1), tibia-tibia (B_1b_1), and femur-femur (C_1c_1) (see Figure 2).

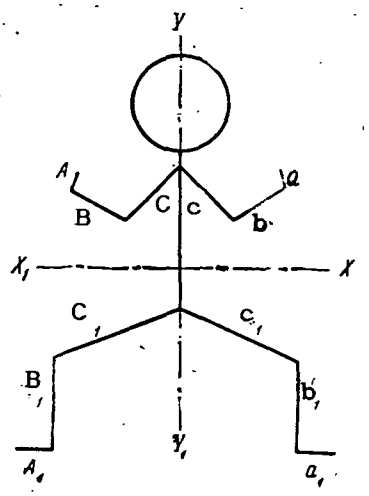

Figure 2. Diagram of the construction of the experiments to investigate the synchronism of synkinesis in man.

In this particular series, the degree of synchronization in the movements of symmetrical, that is, of the same, fingers of the right and left hands were investigated: thumb-thumb, index-index, middle-middle, ring-ring, little-little.

The second series of experiments involved the investigation of the degree of possible synchronization of movements located symmetrically with respect to XX_1; that is, of synkinesis of the lower and upper human extremities: hand-foot (AA_1), forearm-tibia (BB_1), and shoulder-femur (CC_1) (see Figure 2).

The third series studied asymmetrical synkinesis. The degree of possible synchronization of synkinesis of the fingers of one hand (the right) was studied. This series involved finger movements; thumb and index, thumb and middle, thumb and ring, thumb and little, index and middle, index and ring, index and little, middle and ring, middle and little, ring and little. /140

Used for the investigations were people leading active motor lives, many of them regular participants in sports.

The nature of the domestic, professional, and sports activities of the subjects was not associated with movements similar to those used in the experiments. The people who took part had right, as well as left, functional asymmetry.

No special attempt was made to include people with professional skills the nature of which included movements similar to those used in our experiments, machinists and pianists, for example.

Subjects ranged in age from 15 to 29, and included 27 men and women. We recorded 609 oscillograms of synkinesis. All data were processed statistically.

Results of the Investigations

First Series of Experiments

The results listed in Table 1 were obtained from the investigation of the degree of synchronism of right-left side synkinesis completed by the different

links in the upper and lower extremities.

TABLE 1. MAGNITUDE OF HETEROCHRONISM OF RIGHT-LEFT SIDE SYNKINESIS COMPLETED BY THE LINKS OF MAN'S UPPER AND LOWER EXTREMITIES (IN msec)

Body link	Right/ left	Hand-hand	Forearm-forearm	Shoulder-shoulder	Foot-foot	Tibia-tibia	Femur-femur
Statistical processing	$X \pm S_{\bar{x}}$	13.2±1.0	16.5±1.7	18.2±1.9	16.1±2.3	30.2±2.9	26.2±2.2

$\bar{X}$ - mean arithmetic; $aS_{\bar{X}}$ mean error.

The data listed in Table 1 tell us that the degree of heterochronism of movements completed by the links in the arms and legs is in the range from 13.2 to 30.2 msec. These figures characterize the magnitude of the heterochronism occurring when so-called simultaneous movements are made. Analysis of the data listed in Table 1 will show that movement made by the different links of the extremities are synchronized with different degrees of precision. In particular, the degree of synchronization of movements of the links of the arms is of higher degree than that for the movements of links of the legs. The degree of synchronization of movements of the links of the arms were recorded in the range from 13.2 to 18.2 msec, those for the movements of the links of the legs from 16.1 to 30.2 msec. These differences, expressed in mean magnitudes of heterochronism, are 15.9 msec for movements of the links of the arm, and 24.2 msec for links of the leg. This means that the precision with which links of the arm are synchronized is greater than the synchronization of movements made by the symmetrical links of the legs by a factor of more than 1.5. Further analysis of these data shows that the movements of the links of the right and left arms with respect to each other are synchronized with different degrees of precision, just as in the case of the links of the right and left legs. Greatest synchronization precision was observed during synkinesis of the right and left hands (13.2 ± 1.0 msec), and the least for movements of the right and left shoulders (18.2 ± 1.9 msec). Synchronization of the movements of the links of the right and left feet were (16.1 ± 2.3 msec). The least degree of synchronization was recorded for synkinesis of the right and left tibias (30.2 ± 2.9 msec). Differences such as these in the degree of synchronization are apparent in terms /141

of direction of shifts when evaluating the mean magnitudes, but are small in absolutes. Table 2 lists the reliability of the different mean arithmetic magnitudes of heterochronism of movements of the links of the right and left extremities.

TABLE 2. STATISTICAL RELIABILITY OF THE DIFFERENCES IN THE MAGNITUDES OF THE HETEROCHRONISM OF SYNKINESIS FOR THE LINKS OF MAN'S RIGHT AND LEFT EXTREMITIES

Hand-hand					
$p > 0,05$	Forearm-forearm				
$0,05 > p > 0,01$	$p > 0,05$	Shoulder-shoulder			
$p > 0,05$	$p > 0,05$	$p > 0,05$	Foot-foot		
$p < 0,001$	$p < 0,001$	$0,01 > p > 0,001$	$p < 0,001$	Tibia-tibia	
$p < 0,001$	$0,01 > p > 0,001$	$0,01 > p > 0,001$	$0,01 > p > 0,001$	$p > 0,05$	Femur-femur

p - level of significance of the differences in the mean arithmetic magnitudes (when $p < 0.05$, the differences are reliable).

The reliability of the quantitative differences taken from the table is determined at the point of intersection of the horizontal lines and the vertical columns, the captions for which correspond to the symmetrical body links studied.

Statistical processing resulted in determination of the reliability of the quantitative difference in a particular series of experiments and developed certain additional factors. In addition to the observed tendency to some deterioration in the indices for the synchronization of synkinesis of the distal and proximal links of the extremities, the absolute magnitudes of heterochronism of the movements of the right and left forearm and shoulder, and of the right and left femurs and tibias, are statistically unreliable ($p > 0.05$).

There is yet another fact that stands out clearly, telling us that the degree of arbitrary synchronization in the case of symmetrical movements of the right and left hands and of the right and left feet, is quite close for the two,

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despite the somewhat larger magnitude of heterochronism for foot movements (16.1 msec as compared to 13.1 msec), but this difference is statistically unreliable. One is led to believe that this fact is so because in real life man often runs into situations in which the need to synchronize the movements of these links of the extremities is sharply expressed. This would be the case, for example, when jumping, or kicking with the feet, or throwing with the arms. In cases such as these, just how precise will be the synchronization of the final movements of kicking with the feet, and of throwing a ball with the arms, will depend on the precision effect of the movement as a whole. Determining the links in the human body for which a greater or a lesser degree of synchronization is possible in synkinesis created the task of explaining whether or not a greater degree of synchronization would be possible for the movements of any parts of the body. This led to experiments in which synkinesis was carried out /142 for the same fingers of the right and left hands. It was assumed that the fingers of hands specialized in doing fine and coordinated complicated motor acts could be synchronized for arbitrary movements with a greater degree of precision than movements of other of the body's symmetrical links. Table 3 lists the results.

TABLE 3. MAGNITUDE OF HETEROCHRONISM OF RIGHT-LEFT SIDE SYNKINESIS PERFORMED SIMULTANEOUSLY BY FINGERS (msec)

Fingers	Right/left	Little-Little	Ring-Ring	Middle-Middle
Statistical processing	$\overline{X} \pm S_{\overline{X}}$	14,6±1,2	19,3±1,5	16,0±2,4

The data listed in this table show that the degree of arbitrary synchronization of synkinesis of the fingers is, on the whole, higher than in the case of movements made by other parts of the body. The magnitude of the heterochronism of movements of the fingers is much smaller than in the case of synkinesis of movements of the leg links. This comparison, in mean figures, is presented by the magnitudes 24.2 msec for symmetrical leg links and 14.9 msec for symmetrical fingers. A like comparison in mean magnitudes of the degree of heterochronism of the arm links and of the fingers shows 16.0 and 14.9 msec, respectively. But

of equal interest is the analyssis of the feasibility of synchronizing the movements of individual fingers. This comparison shows that the movements of the index fingers can be synchronized most precisely of all. The magnitude of the heterochronism is less in this case, 11.0 msec (see Table 3). Synchronism of the movements of the thumbs and little fingers of the right and left hands is not as good, with the heterochronism 13.8 and 14.6 msec, respectively. Most poorly synchronized in the experiments were the movements of the right and left ring fingers, where the heterochronism was 19.3 msec, that is, much higher than that observed during symmetrical movements of the links of arms and feet.

Statistical processing developed a group of fingers, the arbitrary synchronization of the movements of which is comparatively high. This group comprises the movements of the index, thumb, and little fingers. A second group includes the comparatively poorly synchronized movements of such of the fingers as the middle and ring. The difference in absolute magnitudes of the heterochronism of the movements between these groups is statistically reliable. Thus, movements of the index fingers of the right and left hands can be synchronized with even greater precision than can symmetrical movements of the hands.

Second Series of Experiments

The degree of synchronization of the synkinesis of the links of the right half of the body, symmetrical relative to the horizontal axis of symmetry (YY_1) was used. Synkinesis of the links of the upper and lower extremities, hand and foot, forearm and tibia, shoulder and femur, was performed for this purpose. Table 4 lists the results of these investigations. /143

TABLE 4. MAGNITUDE OF THE HETEROCHRONISM OF SYNKINESIS PERFORMED BY THE LINKS OF THE UPPER AND LOWER EXTREMITIES OF THE RIGHT HALF OF THE BODY (IN msec)

Body link	Arm-Leg	Hand-foot	Forearm-Tibia	Shoulder-Femur
Statistical processing	$\bar{X} \pm S_{\bar{X}}$	17,8±3,9	25,6±4,2	39,2±7,5

These data show that the degree of synchronization of the movements of the links of the upper and lower extremities is much worse than the right-left side movements. This is readily apparent from a comparison of the data in Tables 3 and 5.

The degree of synchronization of the movements in the large joints, symmetrical with respect to the vertical axis (YY_1), is in the range from 13.2 to 30.2 msec, whereas the degree of arbitrary synchronization for movements symmetrical with respect to the horizontal axis (XX_1) is in the range from 17.8 to 39.2 msec. The facts obviously are that conditions for coordination of simultaneous movements of the upper and lower extremities are more difficult. Attempts to determine if the upper or lower extremities largely lead the synkinesis of another link were futile. A link leading the synkinesis of some other part of body can be a lower, or an upper, extremity with equal probability. Analysis of the degree of synchronization of the different links of the upper and lower extremities permits the comment that movement of hand and foot can be synchronized with a higher degree of precision, and the movements of the shoulder and femur can be synchronized with least precision of all. The heterochronism is 17.8 to 39.2 msec, respectively. Statistical processing of the data confirmed this. The differences in the mean arithmetical magnitudes of heterochronism for hand-foot movements, and for shoulder-femur movements, are statistically reliable when $0.05 > p > 0.01$.

Thus synkinesis completed with respect to the horizontal axis of symmetry, that is, movements of the links of the upper and lower extremities, can be synchronized with less precision than movements symmetrical with respect to the vertical axis of symmetry.

Third Series of Experiments

Naturally, special interest is found in the possibility of synchronizing asymmetrical movements, particular the synkinesis of the fingers on one hand. This is in addition to the study of the degree to which it is possible to synchronize movements of symmetrical body links. The question was studied in a third series of experiments.

Table 5 lists the results. The data show that synkinesis of the fingers of one hand can be synchronized with greater precision that can all of the potential combinations of movements made by the other body links.

TABLE 5. MAGNITUDE OF HETEROCHRONISM OF SYNKINESIS COMPLETED BY THE DIFFERENT FINGERS (IN msec)

Little				
10,4±1,8	Ring			
19,2±1,4	6,1±0,9	Middle		
13,4±2,9	20,1±3,3	6,0±0,9	Index	
21,3±4,3	22,4±1,9	21,0±3,2	10,4±1,4	Thumb

The degree of heterochronism in the variants of finger movements studied can be as high as 6.0 and 6.1 msec (see Table 5), whereas the least magnitudes of heterochronism were 11.0 msec when the same symmetrical movements of the right and left fingers were synchronized. Analysis of the results of this series of experiments yields yet another peculiarity in the coordination of finger synkinesis. This is the best synchronization of the movements made by a series of finger positionings; movements of the little and ring, ring and middle, middle and index, and index and thumb, the degree of heterochronism of the movements of which was 10.4, 6.1, 6.0, and 10.4 msec, respectively (see Table 5). Characteristic too is the fact that the degree of possible synchronization continues to worsen with combinations of movements of fingers spaced further apart, by one, or by two fingers. The magnitudes of the heterochronism of the synkinesis of little and ring fingers, little and middle, little and index, and little and thumb were increased accordingly; 10.4, 19.2, 13.4, and 21.3 msec (see Table 5). Statistical processing of the data in this series made it possible to separate pairs of fingers, movements of which can be synchronized with maximum precision; middle-little, and middle-index. Movements of the ring-little, and index-thumb, can be synchronized with somewhat less precision. The differences in the magnitudes of the heterochronism of these pairs are statistically reliable. As a whole, the synchronization of the movements of a series of finger positions always is higher, is statistically reliable, and differs from the magnitudes of heterochronism of movements of fingers further apart.

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Discussion of Results

Discovering the potentials and limitations of the arbitrary coordination of movements of the links of the human body is a big problem, one that is not yet solved. Generally accepted is the fact that control functions in living organisms are performed in a manner that is very nearly perfect.

Study of the mechanisms and principles involved in the control of human motor apparatus is one of the real, promising, and practically necessary directions the research should take.

This paper has studied the potentials of arbitrary synchronization of synkinesis in man. The elementary flexing and extension single-joint movements of the different body links have been studied. Synchronism of the work of the symmetrical parts of the body had earlier drawn the attention of physiologists. L. N. Katz, in 1925 [1], noted the lack of synchronism of the /145 phase of contraction of the right and left auricles and the right and left ventricles of the heart. He established the fact that the active phase of the contraction of the muscle of the right and left heart does not begin and end at the same time. And the right half of the heart, the auricle and the ventricle, is involved by excitation 15 to 20 msec before the left. The data in [2, 4] are similar. Comparing these data with ours, it should be noted that in addition to the very close factual data on heterochronism, 6-35 msec in our experiments, and 15-20 msec in the research done by foreign authors, there is a principal difference in the facts compared. It is that the peculiarities of controlling the functioning of the right and left heart can be characterized by a unilateral upset in synchronism of function. One half of the heart always leads the other in terms of time. This phenomenon can be defined as a stable shift in phase in the functioning of these symmetrical parts of the heart. But in our investigations symmetrical synkinesis is heterchronous, with no definite temporal shift in the beginning of the contact of right or left, or lower or upper, parts of the human body. This means that upset in synchronism may occur with equal probability for the leading, or lagging, time of contact. This fact drew our attention even more because people with right-side as well as left-side functional asymmetry took part in the experiments. This means it can be thought that the anatomical factor, the different lengths of the conducting paths over which nerve impulses are propagated, is not the determinant for the exposure

of that link, right or left, lower or upper extremity, largely responsible for upsetting the synchronization of synkinesis.

The factual material in this paper allows one to talk of the impossibility of precise synchronization of arbitrary movements combined from two links. What this means is that all arbitrary synkinesis in man is heterochronous in the strict sense of the word.

This conclusion is quite apparanet from methodological positions. We can always find the magnitude of the asynchronism from the increase in the precision with which time intervals are recorded. Physiologically, this fact is of interest primarily because it permits the making of a quantitative determination of the minimum time intervals with which the arbitrary control of movements will become impossible for man. The rate of flow of the physiological processes providing for the perception and processing of current information, and the rate of flow of the control process, should be compatible. In other words, current correction of the movement is impossible.

It is natural to assume that difficulties in the synchronization of these movements will be determined by the precision of the differentiations of motor and other analyzers making corrections to the position of the body link in space, and not by the time factor, during synkinesis at very slow rates of displacement of the links. Practically speaking, the experimental materials obtained are significant in that they enabled us to determine those numerical boundaries of the magnitudes of heterochronism with respect to which arbitrary synkinesis can conditionally be broken down into simultaneous and time-different. This conditional breakdown is justified for practical purposes because the requirements with respect to the precision of synchronization of arbitrary movements can differ. But if we assume much more difficulty in carrying out the assignment when the requirements for precision in the synchronization of synkinesis are made more rigid, the goal can be reached only with some predetermined degree of probability that will be different for the different body links.

The physiological basis of heterochronism of synkinesis we observed is anatomically and functionally asymmetrical, and is shown conclusively in many papers; [5-7] and others. /146

It is desirable, in addition to this general factor, to distinguish three concrete factors which in turn can determine the greater or lesser magnitudes of the heterochronism of combined movements.

The first is the habit of the movement, that is, the frequency with which the movements of interest are repeated during work and domestic activities. The second factor is the difference in the precision of the spatial and temporal differentiations that take place in man in the course of realization of movements of the different body links. Given these positions, the fact of more precise synchronization of the movements of the arm links with each other as compared to the combination movements of the leg links, becomes clear. The upper extremities are specialized in performing finer work, from the standpoint of coordination. This principle can be explained by the high degree of precision in the synchronization of movements of the fingers as compared to movements of the arm links.

The third factor is spatial concentration; the closer the links of synkinesis are located with respect to each other, the higher the degree of synchronization. Drawing some analogy, we can say that the closer they are to the possibility of triggering and controlling these movements "from one pushbutton," the more precise the external effect of the movement. In this case the control problem is much simplified when the lengths of the paths traveled by the nerve impulses are comparatively the same. This is the case, for example, when providing a high degree of synchronization of the movements of the fingers on one hand located next to each other; middle and ring, middle and index. What this means is that a long length of the common nerve path traveled by the slave impulses provides more precise synchronization of movements. Given these positions, the fact of maximum heterochronism observed for combined movements of the leg links with those of the arms becomes more understandable. The presence of anatomically sharply differing lengths of paths carrying efferent nerve impulses determines the additional difficulties involved in controlling the synkinesis of the links in the upper and lower extremities.

Thus, these peculiarities of control of different links in the human body must be taken into consideration when organizing, and, naturally, when evaluating, the quality of the work done by the man-operator in those situations when he must control several processes taking place in parallel and

regulated by motor acts.

On the whole, this methodology for evaluating the coordination of the movements of the different body links can reveal the functionally more or less preparatory nerve connections between the centers for controlling the links of the motor acts.

Conclusions

1. Arbitrary combined movements of man are heterochronic. The degree of heterochronism differs for movements of different body links.

2. Synkinesis symmetrical relative to the vertical axis of symmetry can be synchronized more precisely than movements made with respect to the horizontal axis of symmetry.

3. Symmetrical synkinesis of the arm links can be synchronized with more precision that synkinesis of the leg links.

4. Symmetrical synkinesis of the links of man's upper and lower extremities /147 can be synchronized, but best is for the distal, worst for the proximal.

5. Synkinesis of the fingers can be synchronized more precisely than can the movements of other links of the extremities. At the same time, synchronization of synkinesis of the fingers of one hand is better than for movements of symmetrical, that is, the same, fingers of the right and left hands.

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